



# Antiquity of aridity in the Chilean Atacama Desert

Jonathan D.A. Clarke\*

*CRC LEME, Department of Geology, Australian National University, ACT 0200, Australia*

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## Abstract

The Atacama Desert of northern Chile and southern Peru has one of the longest histories of arid conditions known. Although most studies have focused on the hyper-aridity prevalent since the Miocene, all terrestrial sediments in the region from the late Triassic onwards also record evaporitic and thus arid climates. Supergene mineralization in the region did not develop under a more humid climate conducive to deep weathering, but under arid conditions. These processes may have been facilitated by hydrological changes during Miocene uplift and drainage incision, but were operational prior to the uplift. Similarly, global cooling and changes to oceanic circulation in the post Miocene period only accentuated existing conditions. A whole regolith perspective is vital to understanding the history of aridity in the Atacama Desert and its relevance to arid zone morphogenesis, regolith formation, and supergene mineralization. In particular, the long history of aridity raises the possibility that supergene mineralisation, under the appropriate conditions, form in arid environments, instead of requiring humid conditions.

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## 1. Introduction

The Atacama Desert is the driest desert in the world. Arica and Iquique (see Fig. 1 for locations of local place names in the text) have annual rainfalls of only 0.5 and 0.6 mm, respectively, while Antofagasta, Calama, and Copiapo receive 1.7, 5.7, and 12 mm each (Dirección Meteorológica De Chile, 2000). The Atacama Desert is the result of the confluence among

the subtropical high-pressure zone, the cold Humboldt current along the coast, and offshore winds. This extreme aridity has resulted in a number of usual and unique features. These include the very low rates of erosion (Nishiizumi et al., 1998) and accumulation of a range of unusual salts, including perchlorates, iodates, and nitrates in the soils, as well as the more common halite, gypsum, and anhydrite (Ericksen, 1981, 1983; Bohlke et al., 1997).

Understanding of the regolith environment and its history is critical to effective mineral exploration in the area (Herail et al., 1999; Cameron et al., 2002). The area also hosts many of the world's most significant porphyry copper–gold ore deposits, which are

\* Current address: CRC LEME, Geoscience Australia, PO Box 378, Canberra, ACT 2601, Australia.

E-mail address: [Jon.Clarke@ga.gov.au](mailto:Jon.Clarke@ga.gov.au).

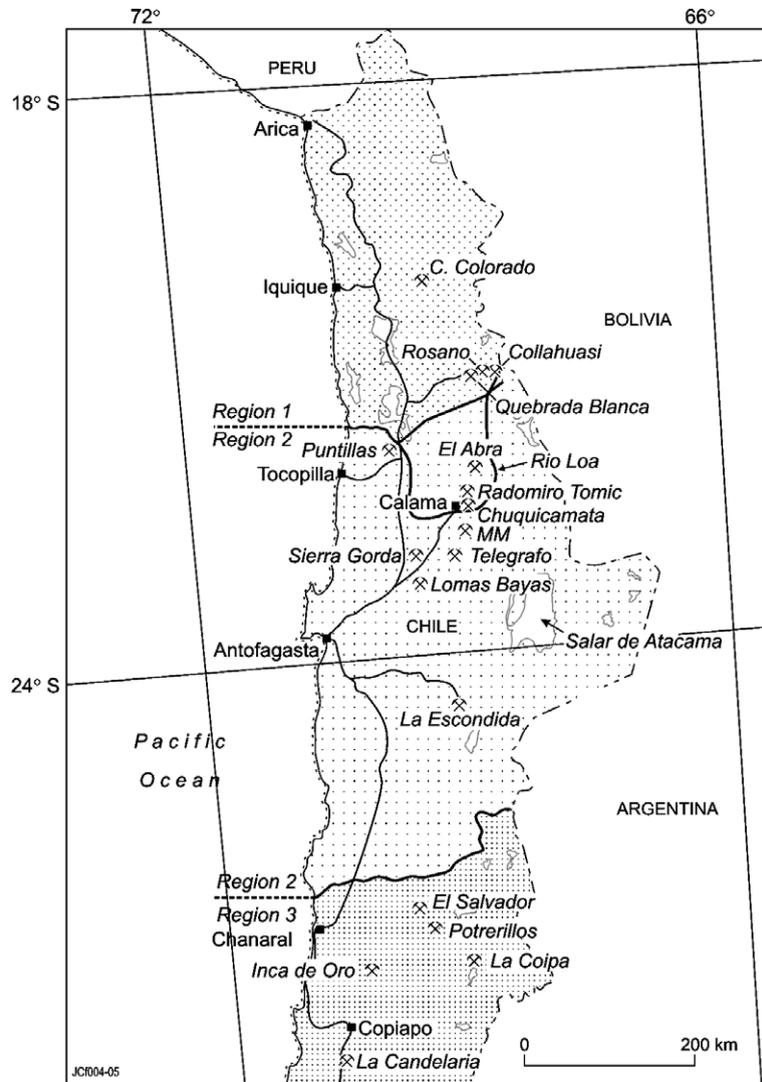


Fig. 1. Cultural localities in northern Chile mentioned in text. Regions 1, 2 and 3 refer to Chilean administrative zones.

low-grade disseminated copper–gold mineralisation in the alteration zones surrounding shallow (often porphyritic) felsic–intermediate intrusions. The economic viability of these deposits is often determined by supergene enrichment zones (Sillitoe, 1989), where weathering of primary (or hypogene) disseminated sulphide mineralisation has resulted in formation of higher grade caps of secondary copper sulphides, oxides, hydroxides, carbonates, sulphates and chlorides. Some deposits also have undergone “exotic mineralisation”, which consists of sub-horizontal secondary mineralisation formed by precipitation of lea-

ched copper at some point down the groundwater gradient from the hypogene mineralisation (Mote et al., 2001). The presence of these secondary mineralization zones is a reflection of the history of groundwater, tectonics, landscape, and climate of the Atacama (Brimhall and Mote, 1997; Mote and Brimhall, 1997; Mote et al., 2001). The supergene zones date mostly between the Early Oligocene and Mid Miocene, apparently defining a “supergene time window” (Segestrom, 1963; Mortimer, 1973; Sillitoe and McKee, 1996). The extreme aridity of the climate and unusual mineralogy of the regolith is also of consider-

able interest because of its value as an analogue to the Martian surface (McKay et al., 2003). The margins of the Atacama Desert also offer the potential to be sensitive records of climate change (e.g. Bobst et al., 2001; Latorre et al., 2003a,b). In the last 10 years there has been a major increase in research into the Atacama Desert for these reasons, and an explosion of data.

This paper provides a brief outline of the geomorphology and regolith architecture of the Atacama Desert and then examines the climatic conditions implicit in the depositional environments of onshore and marginal marine sediments from the Late Triassic to the present, based mainly on a review and reinterpretation of the literature published so far. It closes with a brief discussion on the significance of Quaternary climate fluctuations on the overall aridity of the region, and possible implications for the genesis of supergene mineralisation.

## 2. Regolith and landforms

### 2.1. Physiography and general geology

The physiography of the Atacama Desert in Chile consists of several components (Figs. 2 and 3) including a coastal range (Cordillera de la Costa) separated from the Precordillera by the Central Depression (Valle Centrale). The Preandean basins separate the Precordillera from the Andes proper (Valero-Garces et al., 1999). The Cordillera de la Costa consists of Mesozoic igneous and sedimentary rocks. The Precordillera is composed of Mesozoic to Eocene rocks. The Valle Central consists of a basin filled by Oligocene to Pliocene sediments (Sillitoe et al., 1968). Miocene to Holocene sediments fill the Preandean basins.

### 2.2. Surfaces

The Cordillera de la Costa is characterized by high relief on all scales and active faulting along structures such as the Atacama fault (Fig. 4A). The high relief along the coastal ranges contrasts with the smooth, duricrusted surfaces further inland. This is probably due to strong salt weathering under the influence of periodic coastal fogs, the *camanchaca* (Goudie et al., 2002).

Much of the Valle Centrale consists of a relict surface of Late Tertiary age. Maximum ages are set by the age of volcanic materials within the surficial sediments of depositional surfaces. In the Arica area in the north of Chile contain pyroclastic units dated at 2.9–3.0 Ma (Vogel and Vila, 1980) while further south equivalent sediments in the Calama region contain Late Miocene pyroclastics (5.6–8.9 Ma; Marinovic and Lahsen, 1984). Still further south at El Salvador, the land surface is older again, as it consists of sediments with 11.5 Ma pyroclastics (Clark et al., 1967; Sillitoe et al., 1968).

The land surface is gently undulating, duricrusted, and deflated (Fig. 4B). Because of limited dissection the duricrusts are rarely exposed as breaks in slope as they commonly are in other parts of the world. The extensively deflated surface consists of fragments of gypsum duricrust, andesitic pebbles, and a lag of lithic sand. Stone circles and polygons form a network of stones enclosing areas of bare ground. These are locally common in a number of areas. Circular, convection-like movements of the soil driven by heating–cooling and wetting–drying cycles are thought to form these patterns. These, and the more or less horizontal stripes of stone concentrations present on some slopes may be due to a combination of soil circulation with, in the case of the stripes, down-slope creep (Beatty, 1983). Cosmogenic isotopes locally yield exposure ages for alluvial fans deposited on this surface of 3–4 Ma (Nishiizumi et al., 1998). This supports the antiquity of the land surface deduced by Alpers and Brimhall (1988) who measured K–Ar ages of tuffs in soils at Escondida as between 4 and 9 Ma. Even older ages have been obtained by Dunai et al. (2005) who reported cosmogenic exposure ages of 25 Ma from barely eroded depositional surfaces in the Cordillera de la Costa.

The surface of the northern part of Valle Centrale has been locally deeply dissected by quebradas (canyons, Fig. 4C), in some cases up to 1.5 km deep, but typically less than 1 km (Mortimer, 1980). Their incision postdates deposition of the Late Tertiary valley-fill sediments of the Valle Centrale succession. Only the trunk drainages of the quebradas contain actively flowing or intermittent streams. Some tributaries are relict and contain no evidence of recent flow or even of relict fluvial sediments along their floors (Fig. 4D), and may have been shaped, at least partly,

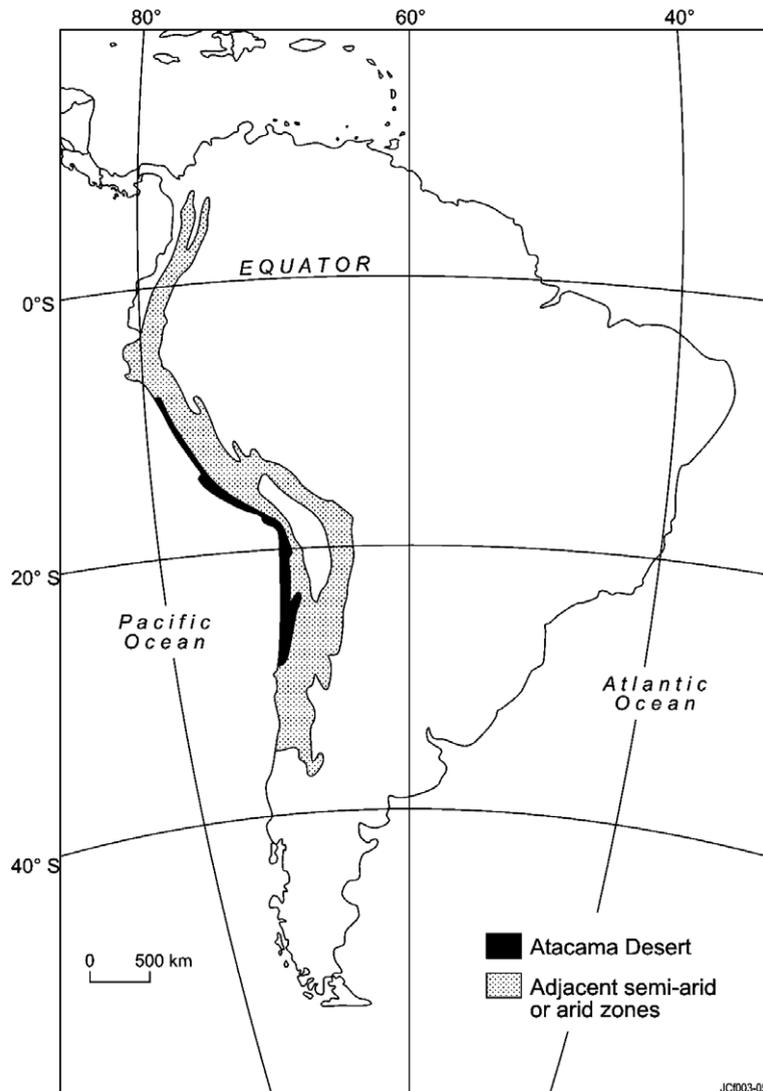


Fig. 2. The Atacama Desert and its semi-arid fringe.

by groundwater sapping (Hoke et al., 2004). Exposure ages on the walls of some of the quebradas are of the order of >300 ka (Nishiizumi et al., 1998), indicating very low erosion rates since the mid-Pleistocene.

The landscape of the Pre-Andean basins contrasts markedly to that of the Valle Centrale. While parts of some of these basins, such as the Atacama Basin (Munoz and Townsend, 1997; Munoz et al., 1997), have experienced ongoing deposition, adjacent areas are currently undergoing deformation. This has resulted in the inversion of evaporitic Miocene sedi-

ments, most spectacularly in the Cordillera de la Sal (Wilkes and Gorler, 1988), synchronous with continued deposition in the Salar de Atacama. The extreme aridity of the area is such that it allows halite to be a ridge forming lithology, accentuating the structural complications.

### 2.3. Duricrusts

Duricrusts are a common feature on the inland slopes of the coastal range and the Valle Centrale.

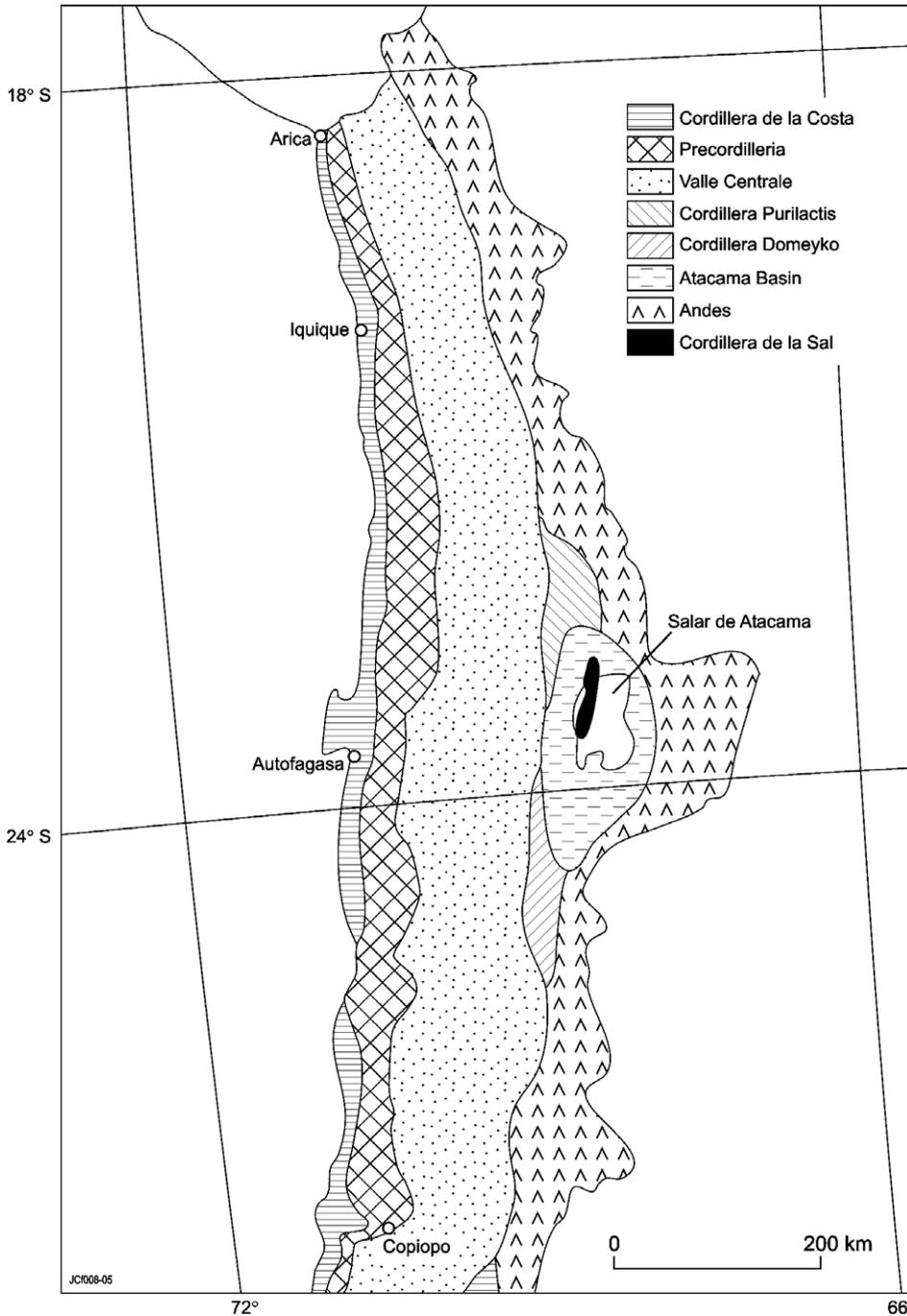


Fig. 3. Physiographic features mentioned in text.

Salts occurred either as fabric-preserving cement or as fabric destructive nodules and masses. The preserved fabric consisted on original depositional textures of

alluvium or colluvium (see [Ericksen, 1983](#)). The two styles may simply be end-members of a progression. Where extensive precipitation of salts has destroyed

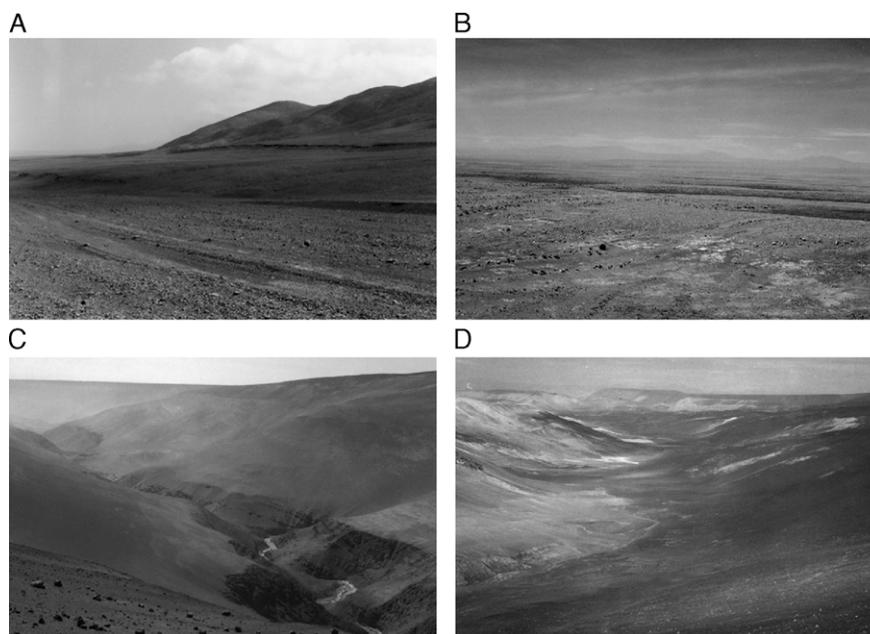


Fig. 4. Field photos (1). (A) Atacama landscape, showing trace of Atacama fault (small ridge), north east of Antofagasta. (B) Deflated and duricrusted surface, Pampa de Chiza, south of Arica. (C) Lower reaches of Quebrada de Chiza, south of Arica, showing smooth, covered slopes of Neogene sediment and bare rock in Mesozoic basement in lower part of quebrada. (D) Dust and duricrust mantled inactive tributary of Quebrada de Chiza.

the original fabric the coarse fraction appears to have been expelled to the surface. Because dissection is so limited, duricrusts are best exposed in workings for nitrates and other salts, or on dissected slopes where erosion has exposed slope duricrusts (Fig. 5A).

Sulphate duricrusts are found on the inland slopes of the coastal ranges and in the Valley Centrale. Those of the Valle Central may be impregnated by exotic salts, such as nitrates, perchlorates, and iodates (Ericksen, 1983). Calcium and sulphate in the soils is due to rock weathering and groundwater remobilisation weathering, rather than accession as cyclic salts, followed by aeolian redistribution in the landscape (Rech et al., 2003a). Sulphate duricrusts are absent from the comparatively higher rainfall areas of the Cordillera ranges. Further south, towards Copiopo, sulphate duricrusts are replaced by calcretes. The origin of the nitrate salts has been the subject of much controversy (e.g. Ericksen, 1981, 1983), however the most recent geochemical studies appear to confirm deposition of atmospheric nitrate as the source (Bohlke et al., 1997; Michalski et al., 2004).

A common architecture occurs where fluffy gypsum impregnated soils overlie more massive anhydrite-cemented material. This occurs in areas of deflation. It may represent progressive surface hydration of the anhydrite by surface moisture (chiefly fog) as the ground surface is lowered. Another common architecture is, where the desert pavement is weakly cemented by a thin sulphate crust, it overlies a more powdery dust layer. This is in turn underlain at a depth of a few centimetres by a polygonally cracked sulphate hardpan. Salt distribution in the duricrust appears controlled partly by topography, at least in a gross sense. Calcium sulphates occur in all positions in the landscape and their formation of a duricrust may be partly due to accession by windblown dust. This is supported by isotopic evidence (Rech et al., 2003b). Sodium sulphates seem to occur in mid-slope positions, possibly by concentration down-slope of sodium in vadose water. Halite occurs only in the lowest part of slope sequences, both in valleys and as nodular to crustose precipitates from groundwater in playas. Locally, however, halite can also form

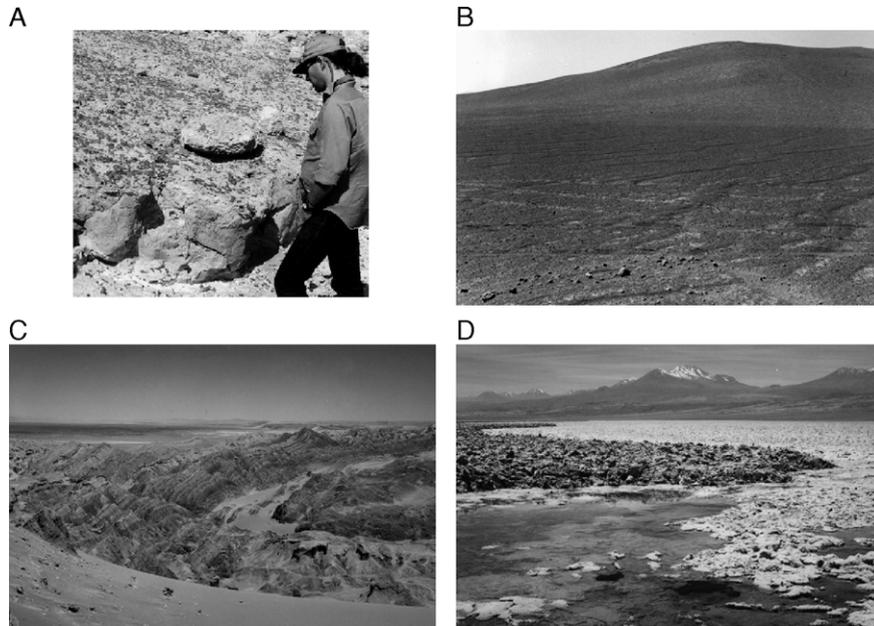


Fig. 5. Field photos (2). (A) Anhydrite duricrust exposed in eroded slope, Agua Blanco. (B) Dust and duricrust mantled hills near Quebrada Honda, east of Antofagasta, note gravel wind ripples on floor of valley. (C) Halite-capped ridges of the Cordillera de la Sal, east of San Pedro de Atacama. (D) Surface of the southern end of Salar de Atacama, showing groundwater spring vent in foreground and groundwater-fed salt surfaces with increasing roughness corresponding to increasing age. Andes Mountains in the background.

duricrusts on slopes (Oberlander, 1994). Many playa surfaces are relict, with dust mantles covering the evaporites.

#### 2.4. Surface processes

Some ongoing processes do affect the present surface, despite its antiquity. Some rivers, such as the Rio Loa, which are fed by snowmelt from the Andean Highlands, are still actively eroding the surface. Modern alluvial fans are locally common, especially along the eastern margins of the desert (Berger and Cooke, 1997; Rech et al., 2002). Other quebradas appear relict, with aeolian reworking and mantling of their floors. Accession by aeolian dust, rich in sulphates (Rech et al., 2003b), is also important, resulting in the smoothed appearance of the landscape and hills of the Valle Centrale (Fig. 5B).

Erosion by mass wasting appeared confined to the steeper portions of hills with exposed outcrop. Gully-confined debris flows, apparently formed during very rare rainfall events, appear to have been the most significant form of mass wasting. Falls and slides

are active only on the steepest slopes, particularly along the coast. Cemented mantles of wind-laid sulphate-rich dust appear to have armoured many slopes further inland from falls and slides.

### 3. History of aridity

The primary source of data on the history of aridity in the Atacama Desert is in the mostly terrestrial sediments of the region. The relevant stratigraphic and sedimentological data is summarized in Table 1.

#### 3.1. Triassic

The earliest evaporites in the Atacama Desert are Late Triassic–Early Jurassic (pre-Sinemurian) and are described by Suarez and Bell (1987). The Cifuncho Formation contains anhydrite cemented and veined volcanic conglomerates deposited in alluvial fan environments. The Pan de Azucar Formation of a similar age has casts of hopper halite in the basal

Table 1  
Sedimentary history of aridity in the Atacama Desert, illustrated by representative stratigraphic units

Stratigraphic units	Age	Lithology	Depositional environment	Sources
Unnamed units in Salar de Atacama	Pliocene–Holocene	Evaporites and clastics	Evaporitic lakes (such as Salar de Atacama)	Munoz and Townsend (1997), Munoz et al. (1997)
Hilaricos and Soledads evaporates	Plio–Pleistocene	Anhydrite, halite, gypsum	Continental playa lake	Pueyo et al. (2001)
San Pedro Group	Oligocene–Middle Miocene	Mudstone, gypsum, anhydrite, halite	Continental evaporitic lake	(Dingman (1967), Flint (1985), Wilkes and Gorler (1988)
Purilactis Formation	Late Cretaceous–Paleocene	Conglomerate, mudstone, andesitic volcanics, gypsum, halite	Westerly derived alluvial fans feeding into playa lakes	Marinovic and Lahsen (1984), Ramirez and Gardeweg (1982) Hartley et al. (1985)
Quebrada Monardes Formation	Early Cretaceous	Siltstones, sandstones, limestones, gypsum, halite casts	Coastal saline lagoons	Suarez and Bell (1987)
Caracoles Group	Early Jurassic	Limestone, sandstone, calcareous and bituminous shale, anhydrite, gypsum	Marine to evaporitic marginal marine	Marinovic and Lahsen (1984), Ramirez and Gardeweg (1982)
Pan de Azucar Formation	Late Triassic	Felsic pyroclastics, sandstone, limestone, gypsum	Fluvial overlain by marine sediments	Suarez and Bell (1987)
Chifuncho Formation	Late Triassic	Conglomerates, felsic–intermediate volcanics, limestone, sandstone, halite casts	Alluvial fan	Suarez and Bell (1987)

part of the Formation. The casts occur in sandstone interpreted as braided river deposits and are overlain by a shallow marine succession. Earlier terrestrial deposits, from Late Permian–Early Triassic Tuina and El Bordo Formation (Ramirez and Gardeweg, 1982), are all non-evaporitic, indicating humid climates prior to the Late Triassic.

### 3.2. Jurassic

Early Jurassic (pre-Kimmeridgian to Kimmeridgian, possibly as early as Bajorcian) evaporites occur in the Caracoles Group (Ramirez and Gardeweg, 1982; Marinovic and Lahsen, 1984). These consist of anhydrite and gypsum closely associated with terrestrial and marine clastics and marine limestones. They were probably deposited in coastal lagoon or sabkha environments. Late Jurassic evaporites occur at modern latitudes of 21–35°S (Suarez and Bell, 1987), which are close to the Quaternary distribution of 19–27°S, indicating that there has been little latitudinal shift of South America and the climatic arid zone over this period, although the Jurassic zone was twice as wide as the Quaternary.

### 3.3. Cretaceous

Early Cretaceous marine and non-marine evaporites occur along the contact between the Lautaro and Quebrada Monardes formations in the southern Atacama (Suarez and Bell, 1987). The evaporites mark the transition between shallow marine limestones of the Lautaro Formation and the continental red sandstones of the overlying Quebrada Monardes Formation. The evaporites are characterised by discontinuous occurrences of cyclic sulphate evaporites. Specific textures present in the host sediment include calcitic and chalcedonic pseudomorphs after anhydrite, chalcedonic pseudomorphs after halite, and anhydrite relicts. The redbeds comprise a complex facies association of mudstones, siltstones and sandstones. The evaporites are interpreted as being the products of deposition in saline coastal lagoon and inland sabkha environments associated with fluvial and aeolian red beds in an intra-arc basin (Bell, 1991; Bell and Suarez, 1993). Like those of the Late Jurassic, Early Cretaceous evaporites occur at modern latitudes of 21–35°S (Suarez and Bell, 1987).

In the northern Atacama the Purilactis Formation of Late Cretaceous to Paleocene age also contains evidence of evaporites (Ramirez and Gardeweg, 1982; Marinovic and Lahsen, 1984). Minor anhydrite nodules in playa lake sediments were described by Hartley et al. (1985) in the Purilactis Formation.

### 3.4. Tertiary

The Oligo–Miocene San Pedro Group is extensively exposed in the Cordillera de la Sal (Dingman, 1967; Flint, 1985; Wilkes and Gorler, 1988). The San Pedro Group contains gypsum, anhydrite and halite, and is perhaps the most spectacular occurrence of Neogene evaporites in the Atacama Desert (Fig. 5C). These have been interpreted as having been deposited in an alluvial-fan to playa-lake environment. Fossiliferous horizons containing limnic algae, ostracods, and gastropods are present in the northern part of the exposure. They indicate either localised incursion of lower salinity water or ephemeral periods of low salinity. Overall, however, the facies are for the most part strongly evaporitic. Halite units several tens of metres thick occur repeatedly in the succession. Oligocene–Miocene evaporites (Suarez and Bell, 1987; Alonso et al., 1991) occur in the modern latitudes of 21–27°S.

During the Neogene evaporate deposits are extremely common and well preserved, because of the comparative youth. In the Valle Centrale of northern Chile a wide range of terminal Plio–Pleistocene evaporate deposits comprise the Hilaricos and Soledad evaporites (Pueyo et al., 2001), and can be taken as representative of deposits of this age.

### 3.5. Quaternary

Pliocene–Holocene evaporites have been and continue to be deposited in modern saline lakes, of which Salar de Atacama is the largest (Fig. 5D). They include gypsum, anhydrite, halite, borates, and sodium sulphates (Stoertz and Ericksen, 1974; Ericksen and Salas, 1989). Evaporites are being deposited in salt lakes and coastal lagoons, between 19°S and 27°S (Suarez and Bell, 1987). Deposition of salts in some of these lake basins has been continuous since the Miocene (Alonso and Risacher, 1996; Munoz and Townsend, 1997; Munoz et al., 1997), for example

halite with a thickness of 975 m has accumulated in Salar de Atacama.

### 3.6. Background of persistent aridity

According to previous research, there are three palaeogeographic reasons why aridity has persisted for the past 200 My. Firstly, the Atacama region has been at approximately the same palaeolatitude during this period. Secondly, the South American continent has maintained the same north–south orientation during this period; thirdly, the region has always been near the western margin of the continent (see Benavides, 1968). This has had three consequences. First, the Atacama region has always been in the subtropical high pressure (and low rainfall) zone. Second, the prevailing winds have always been dry through passage over the continental interior. Third, the continental configuration makes it likely that a cool-water current has always been active off the coast, reducing evaporation (Hartley, 2003).

Other aridity-inducing factors, such as global cooling (Hartley and Chong, 2002), Miocene uplift intensifying the Andean rain shadow, or enhanced upwelling of the Humboldt current and the subsequent reorganisation of oceanic circulation induced by closure of the Central American Seaway in the Pliocene (Hartley, 2003), are comparatively recent impositions. It is important to recognize that, while these factors, whether operating individually or in concert, generated the hyper-aridity experienced in the region, they did not create aridity which has been of very long standing.

## 4. Discussion

### 4.1. How variable were the Atacama climates?

The variability of climate over this ~200 My interval is an important issue. If variability was large enough, arid climates could have alternated with humid ones. Data are lacking on the degree of variability. The variability of Quaternary climates may serve as a proxy, especially as Quaternary variations were probably more intense than those of the longer term past.

There is varying evidence for high lake levels in the salars of the Atacama Desert during the Pleistocene. Unequivocal evidence of freshwater deposition and higher lake levels is lacking for Salar de Atacama (Stoertz and Ericksen, 1974), although periods of perennial saline lakes appear to have occurred (Bobst et al., 2001). In contrast, sediments in Laguna Punta Negra do record episodes of fresh water deposition. Terraces, elevated strand lines, deltas, and lake sediments are present. Palaeolithic archaeological sites occur at the northern outlet of the lake, even though this now discharges only saline water. Lynch (1986) took this as evidence for fresh water discharge in the past. Lynch (1986) cites Hastenrath (1971) and Heusser (1981), who argued that atmospheric circulation was displaced northwards during the Pleistocene. Evidence for this lies in the observation that the present snowline in the Andes rises from east to west north of 31°S, indicating precipitation from the east. Conversely, the Pleistocene snowline (from geomorphological features) rose from west to east at 28°S, indicating precipitation from the west. This pattern occurs today only north of 27°S. The northerly shift in weather patterns confirms the data from the Bolivian Altiplano (Grosjean, 1994; Grosjean et al., 1995).

Short-term but significant fluctuations have also occurred in the Holocene. Fossil rodent middens (Latorre et al., 2003a,b; Rech et al., 2003a) shows evidence for fluctuating vegetation on the margins the arid to hyper-arid regions represented by the Cordillera Domeyko, conclusions borne out by paleohydrological studies (Rech et al., 2003b). The cause of the establishment of temporary wetlands at specific locations such as Quebrada Puripica has been extensively debated. Possibilities include a rise in groundwater level due to climate change (Rech et al., 2003a), damming of the quebrada by landslips (Grosjean et al., 1997), or hydrological changes during long dry spells (Grosjean, 2001). However, the confluence of evidence between increased water levels and an expansion of vegetation supports the concept on short-lived increases in precipitation driven by changes to the South American Summer Monsoon (Rech et al., 2002).

#### 4.2. Environmental extremes

In the Altiplano the last glacial–interglacial cycle has seen extreme variations in annual mean tempera-

ture of approximately 11° and of rainfall of 300 mm (Messerli et al., 1993; Grosjean, 1994; Grosjean et al., 1995). The ground surface has varied from perennial or near perennial snow cover, through the gelisolifluction zone to light vegetation. Lake waters have varied from fresh to hypersaline.

Extrapolation of the Altiplano studies (Messerli et al., 1993, Grosjean, 1994, Grosjean et al., 1995) to the lower altitudes of the Atacama Desert causes some uncertainties, but general trends can be inferred. The altitude–rainfall curve of Stoertz and Ericksen (1974), although crude, does approximate the more refined conclusions of the Altiplano studies. The curve indicates that a rainfall increase of ~250 mm would be sufficient to result in perennial lakes in the Altiplano.

At altitudes below 3000 m, typical of the Atacama, a rainfall increase of this magnitude translates into an increase of 50 mm, assuming a rainfall–altitude relationship similar to that extant today. Evidence of high water levels is limited for lakes in the Atacama Desert proper (Stoertz and Ericksen, 1974), suggesting that any increase in rainfall did not exceed this limit. For the Atacama Desert therefore, a more likely precipitation range would be 0–100 mm during glacial–interglacial cycles. Thus, in general, the climatic changes from interglacial to glacial would have had little impact on the landscape below 3000 m, except in the immediate vicinity of lakes which would have become wetter and on areas elevated above 3500 m which would have experienced gelisolifluction during the colder climates.

The exception would have been in the valley of the Rio Loa. This major river system drains from the Altiplano and any increase in precipitation would result in significant increase in discharge of this river. Stoertz and Ericksen (1974) argue that this would have led to development of deep (75 m) lakes in the Rio Loa Basin. There is evidence from diatomite units in the El Loa Formation that such lakes existed in the Rio Loa basin during the Neogene (Marinovic and Lahsen, 1984), however no evidence for or against such lakes has been reported for the Quaternary.

#### 4.3. Implications for supergene mineralisation

Mineralisation in the Atacama region (Sillitoe, 1989) occurs in three parallel belts from west to east

of Cretaceous (>65 Ma), Paleocene–Early Eocene (65–45 Ma) and Late Eocene–Early Oligocene (40–30 Ma) age. Superimposed on almost all of these deposits is supergene mineralization. Several authors, beginning with [Segerstrom \(1963\)](#) and [Mortimer \(1973\)](#), [Bouzari and Clark \(2002\)](#) have speculated on the existence of a “supergene time window” in the Atacama Desert. These authors suggest that there was a specific time interval (Segerstrom: Middle to Late Tertiary, Mortimer: Late Eocene and Late Miocene, Bouzari and Clark: Oligocene to Miocene) that was particularly favourable for the development of supergene mineralization. They further suggested that an increase in aridity in the late Miocene effectively terminated the development of supergene mineralization.

[Alpers and Brimhall \(1988\)](#) suggested that a change in climate from arid to hyper-arid in the Middle to Late Miocene effectively terminated the development of supergene caps on mineralization. As shown above, there is evidence of evaporite sedimentation in all relevant settings (shallow marine to continental) since the Late Triassic (220 Ma) in northern Chile. Prior to this time sedimentation appears to have been non-evaporitic. Although there are gaps in the record, chiefly during the Middle Jurassic, late Early to early Late Cretaceous, Eocene, and Late Miocene, they are relatively brief. These are gaps, not just in the record of evaporites, but in all sediments. These gaps

are probably due to the ongoing compressive tectonism of the active western margin of South America ([Jordan and Alonso, 1987](#); [Bell and Suarez, 1993](#)), rather than climatic change.

[Alpers and Brimhall \(1988\)](#) dated supergene alunite at 18 Ma (Middle Miocene) at Escondida. [Sillitoe and McKee \(1996\)](#) reported the ages of 25 samples of supergene alunite from 14 ore bodies in northern Chile. Deposits studied included La Coipa, MM, Escondida, Chuquicamata, El Salvador, Collahausi, Telegrafo, Cerro Colorado, Sierra Gorda, Lomas Bayas, Inca de Oro, and Puntillas. Supergene mineralization in these deposits formed in the 15–34 Ma time bracket. This corresponds to the Early Oligocene to Middle Miocene. [Mote et al. \(2001\)](#) dated exotic copper deposits at El Salvador and Chuquicamata, with the former dating at 35–11 Ma and the latter at 17 Ma. The gap between mineralization and supergene formation varied from 4 to 111 My. In general, the older the deposit, the greater the time gap between mineralization and oxidation ([Table 2](#)). At El Salvador the date of the oldest supergene mineralization overlap with the youngest hypogene mineralization, indicating that leaching by regolith processes was concurrent with the later phase of hypogene mineralization.

[Sillitoe and McKee \(1996\)](#) attribute the 5 My minimum time lag between mineralization and supergene formation to the time required to unroof the deposits by erosion. An additional 5–10 Ma is needed

Table 2  
Supergene and exotic mineralization dates in the Atacama Desert

Deposit	Hypogene ore (Ma)	Supergene and exotic ore (Ma)	Number of determinations	Hypogene–supergene/exotic age gap (Ma)	Sources
La Coipa	20–34	15	1	5–9	<a href="#">Sillitoe and McKee (1996)</a>
MM	32–33	20–21	2	12	<a href="#">Sillitoe and McKee (1996)</a>
Escondia	31–35	15–18	4	16–17	<a href="#">Sillitoe and McKee (1996)</a> ,
Chuquicamata	31–36	15–20	8	16	<a href="#">Alpers and Brimhall (1988)</a> <a href="#">Sillitoe and McKee (1996)</a> ,
El Salvador	31–43	38–11	22	–4 to 12	<a href="#">Mote et al. (2001)</a> <a href="#">Sillitoe and McKee (1996)</a> ,
Collahausi	~38	15	1	23	<a href="#">Mote et al. (2001)</a>
Telegrapho	40	20	1	20	<a href="#">Sillitoe and McKee (1996)</a>
Cerro Colorado	~58	30–34	22	24–28	<a href="#">Sillitoe and McKee (1996)</a> ,
Sierra Gorda	63–64	14	1	49–50	<a href="#">Bouzari and Clark (2002)</a> <a href="#">Sillitoe and McKee (1996)</a>
Lomas Bayas	64	21	1	43	<a href="#">Sillitoe and McKee (1996)</a>
Inca de Oro	~66	14	1	52	<a href="#">Sillitoe and McKee (1996)</a>
Puntillas	132	21	1	111	<a href="#">Sillitoe and McKee (1996)</a>

to form the supergene deposits. They concluded that supergene activity throughout northern Chile ceased at 14 Ma. This was linked to the supposed Miocene optimum for weathering and was terminated by intensifying aridity. However, this time frame may be an artefact of preservation. All deposits, except Puntillas, are Cenozoic, and none are younger than Miocene. There is no preserved pre-Miocene weathering profile at Puntillas. Furthermore, palaeoclimates were no more or less arid during this period than before or after, as indicated by the anhydrite and halite in the Oligo–Miocene San Pedro Formation (Wilkes and Gorler, 1988).

This raises the possibility that supergene ore formation may be active today, if conditions are right. Clark et al. (1967) in their study of supergene mineralization in the southern Atacama Desert near Copiapo, argued that supergene profiles developed during periods of dissection, not stability. These authors also showed that mine dewatering triggered renewed oxidation of mineralization, with extensive deposition of supergene minerals in the lower parts of mines. This supports their contention that supergene mineralization preferentially forms during periods of dissection. Periods of enhanced erosion were most likely triggered by tectonism and led to depression of the water table and increased oxidation. More recently Brimhall and Mote (1997) and Mote and Brimhall (1997) emphasised the confluence of Miocene uplift and erosion leading to depression of water tables and enhanced supergene formation. They also obtained late Miocene dates on some supergene and exotic copper deposits, indicating that these processes continued under favourable conditions. Rather than the Atacama landscape being a “matureland” (Seegerstrom, 1963), based on Davis’s (1899) concepts of old, mature, and youthful landscapes, it is better described as a metastable landscape. Supergene processes are quiescent in the regolith unless the stability is perturbed.

## 5. Conclusions

The sedimentary record in the Chilean Atacama Desert indicates that there have been long periods of extensive evaporite deposition under semi-arid to hyper-arid climates since the Late Triassic. Focusing

on the undoubted increase of aridity post-Miocene deflects attention away from this salient fact.

Climate oscillations would have occurred throughout geologic time as they have in the Quaternary. However, unless they were even more extreme than those of the Quaternary, it appears unlikely they would have caused a major shift from arid conditions, except locally through supply of both surface and groundwater.

The Atacama Desert is thus almost certainly the oldest continuously arid region on earth. The implications of this for arid zone morphogenesis, regolith processes, and formation of supergene mineralization are areas for further research. In particular, models of supergene ore mineralisation, which tend to assume more humid conditions, may need re-examination.

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